A NEW METHOD OF DATA REDUCTION FOR SINGLE-SENSOR PRESSURE PROBES

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ABSTRACT
The use of multi-sensor fast-response pressure probes is now relatively common place. Unfortunately, these probes are often larger than ideal. It is for this reason that single sensor probes are sometimes used in investigations of unsteady flow. In use, the single sensor probe must be placed at a number of different orientations to the flow, often achieved by simply rotating the stem of the probe mount. The run time of a given experiment increases in proportion to the number of orientations employed. Furthermore, the number of orientations is usually more than strictly required due to poor conditioning of the experiment. This results in a significant amount of redundant information being available and run-time costs being increased. This paper describes a data reduction technique that reduces the run time cost of using single sensor fast response probes to the minimum. This is achieved by using all of the data obtained in the experiment so that there is no redundancy no matter how many orientations are employed. The method relies on comparing the measured data with the calibration data in order to obtain a best fit between the two datasets.

INTRODUCTION
Multi-sensor fast response pressure probes are often used in turbomachinery investigations (e.g., Cherret et al (1992), Gossweiler et al (1990)). The advent of these probes has been made possible due to the availability of relatively small silicon-based pressure transducers. Due to the size of the silicon sensors, the majority of these probes are made by mounting the individual sensors directly into the probe head. Nevertheless, the resulting probes are often larger than ideal for many facilities (e.g. 2.5 to 6 mm, see Gossweiler et al (1990), Cherret et al (1992)). While these probes may provide data of acceptable quality in relatively large-scale facilities, such facilities are rare. There is no doubt that as the technology improves, the size of these probes will reduce. This will make it possible to use these probes in lower-cost, smaller scale facilities. In the meantime, an alternative solution to the problem of scale is available through the use of a single sensor probe that is placed at several orientations with respect to the flow, often by simply rotating the stem of the probe mount (e.g. Humm et al (1995)).

A single sensor probe can typically be made half to a third of the size of a multi-sensor probe. Alternatively, it can be argued that when probe size does not need to be reduced, conventionally packaged sensors can be employed in single sensor probes with a cost reduction of up to two orders of magnitude when compared to the specially manufactured multi-sensor probes. Of almost equal importance is the fact that because a single sensor is employed, the calibration is simpler and changes in calibration due to ambient changes are easier to accommodate. In addition, the complexity and cost of manufacture are reduced. Furthermore, smaller probes tend to suffer less from dynamic calibration errors (Humm et al (1995)) since they operate at a lower non-dimensional frequency in a given unsteady flow.

There is one significant disadvantage to the use of single sensor pressure probes. In effect, each position yields data equivalent to that from one sensor of a multi-sensor probe. In the case of a three-dimensional flow field, therefore, the single sensor fast response pressure probe must be placed in 4 orientations if the yaw angle, pitch angle, stagnation pressure and static pressure are to be determined. However, due to poor conditioning of the experiment the number of orientations is often higher than what would be strictly required. Furthermore, the run time of a given experiment increases in proportion to the number of orientations employed. The increased cost of testing can be sufficient to prohibit the use of single sensor probes as it can be far greater than the cost of manufacture and calibration of multi-sensor probes. Increasing the run time also increases the probability that the sensor calibration will have altered due to contamination or changes in ambient conditions.

To date, the data reduction technique for the single sensor pressure probe has been based on the premise that each position yields data equivalent to that from one sensor of a fixed-position multi-sensor probe. Therefore, increasing the number of orientations to more than that which is strictly necessary means that redundant information is acquired. This paper proposes a new data reduction technique for single sensor pressure probes. The technique employs all the data obtained in the experiment (i.e., there is no redundancy),
thus the experimental run-time should be reduced to no more than that which is strictly necessary. It is based on the approaches used by several researchers when reducing data obtained with single-sensor hot wires.

**Published work on the application of the “least-squares” method of data reduction**

In the place of an X-wire probe, Fujita and Kovasznay (1968) used a single sensor hot wire probe in a two-dimensional investigation of a stationary flow field. The mean velocity was determined by inspection of the linearised anemometer output as the sensor was rotated with respect to the flow. McGuire and Gostelow (1985) employed an almost identical technique when using a single sensor pressure probe at exit from a centrifugal impeller. More significantly, Fujita and Kovasznay (1968) employed the method of least squares to improve the accuracy of the turbulent moments $u^2$, $v^2$ and $uv$. In a paper which closely follows Fujita and Kovasznay (1968), Bissonnette and Mellor (1974) describe the extension of the above technique to three dimensions. They obtained the mean quantities and all six turbulence moments using a slant-wire probe fixed in several discrete positions.

Both Fujita and Kovasznay (1968) and Bissonnette and Mellor (1974) determined the mean flow angle by searching for the maximum response of the sensor. While this may be acceptable in stationary flows, it will not generally be the case in turbomachinery. Kool (1979) and Kuroumaru et al (1982) extended the approach of Fujita and Kovasznay (1968) and Bissonnette and Mellor (1974) to include the determination of the mean flow vector as well as the six turbulence moments using the method of least squares. These applications were combined with the phase-lock-averaging technique to yield data on the flow at the exit from a rotating bladerow.

Because there is no redundancy, Goto (1991) suggests that with $N$ wire positions, the effective number of ensembles is potentially greater than that employed in the conventional approach of, say, Whitfield et al (1972) but this requires verification. To date, the method of least squares does not seem to have been applied to the reduction of data obtained using fast response pressure probes. This paper describes that first application.

**AN EXAMINATION OF THE “LEAST-SQUARES” METHOD**

**Hot wire anemometer**

In the context of determining the velocity field, the ideal probe exhibits a response to flow angle according to the ‘cosine law’.

$$ E = C \cos \xi $$

where $\xi$ is the angle between the velocity vector $C$ and the sensor-normal direction. This is because these probes would respond to the velocity component that is normal to the sensor. Therefore, when a sensor is placed in two orthogonal positions, the velocity vector can be determined.

In practice, the hot wire anemometer is much closer to the ideal probe than most pressure probes. For this reason, and also to maintain a link to previous work, this paper makes a comparison between data obtained using a single sensor hot wire anemometer and that obtained in the same flows using a single sensor pressure probe.

The experiments were conducted using a calibration for angle obtained for a conventional hot wire probe (Dantec 55P11). The probe was rotated about the axis of the stem so that the effect of angle could be determined. The angular response of the sensor is shown in Fig. 1.

![Fig. 1 Angular calibration for hot wire anemometer](image)

The hot wire anemometer has been used to measure unsteady periodic flows. In each case, the phase-lock averaging technique is used to derive the ensemble-mean velocity $\langle C \rangle$ and flow angle $\langle \theta \rangle$. The basis of the least-squares technique is to minimise the quantity

$$ \chi^2 = \sum_i (\langle E_i \rangle - \langle C \rangle - \langle \theta \rangle, \xi_i)^2 $$

where, for example, $\langle E_i \rangle$ represents the phase-lock-average velocity indicated by the hot wire anemometer and $\xi_i$ represents the orientation of the wire with respect to a fixed axis at the $i$th sensor position. In effect, this can be viewed as matching a rather crude calibration of the anemometer derived from the experiment to the actual calibration of the sensor. This matching takes place at each phase angle. In practice, the angular calibration is assumed to be independent of the magnitude of the velocity so that the above equation reduces to

$$ \chi^2 = \sum_i (\langle E_i \rangle - \langle C \rangle - \langle \theta \rangle, \xi_i)^2 $$

where $f$ is the function in Fig. 1 and $\xi_i$ is 0. Because look-up tables have been employed in the present investigation, the exact form of the calibration curve is not relevant. Nor is the fact that the response of the sensor may not be symmetrical or continuous. Additionally, the fact that the calibration curve may, itself, suffer from random errors is of much less significance that would be the case if a conventional approach were adopted.

Fig. 2 shows how the quantity

$$ \tan^{-1} \left( \frac{V}{U} \right) $$

varies with flow angle. This presents the yaw angle calibration for the hot wire anemometer in conventional terms. The velocities $U$ and $V$ are the effective cooling velocities indicated with the hot wire sensor placed in two orthogonal positions. When using the hot wire anemometer in a conventional manner, the calibration shown in Fig. 2 is used to determine the flow angle with respect to the co-ordinate system defined by the two sensor positions. If only one pair of orthogonal positions is used to determine the flow angle, the flow angle must lie within one quadrant when using the calibration shown in Fig. 2. This is because the hot wire anemometer cannot sense the direction of the cooling velocity components $U$ and $V$. Thus two pairs
of positions must be employed to determine which quadrant the flow vector lies in. This is the situation investigated below.

**Fig. 2 Arctan(V/U) calibration for hot wire anemometer**

**Fast Response Pressure Probe**

The hot wire experiments were repeated using a fast response single-sensor pressure probe. In the case of a pressure probe, the flow angle, the stagnation pressure and the dynamic pressure may be determined. Therefore, a minimum of three positions is required to determine the flow conditions.

Fig. 3 shows a photograph of the pressure probe employed in the present investigation. The probe consists of a Kulite LQ062 transducer embedded within the face of a 60° triangular prism. This particular geometry was chosen because the 60° wedge probe is known to have a capture angle of approximately ±60° (Humm et al (1995)). The transducer was placed sufficiently far from the probe tip that the effects of pitch upon the calibration are not large (see Sims-Williams (1994)). Future investigations use a redesigned probe that will incorporate pitch-sensitivity to measure the 3-D flow field. Fig. 3 shows that the probe is not especially small. In the present context, all that matters is that the probe is small relative to the size of the facility. This criterion is satisfied (see below). A multi-sensor probe of similar construction would not satisfy this criterion as easily.

**Fig. 3 Fast response single-sensor pressure probe**

The probe was calibrated in a suction tunnel downstream of the inlet bellmouth. Fig. 4 presents the calibration of the pressure probe assessed here. The response is plotted in the form of the coefficient

\[ C_p = \frac{P_{\text{sensor}} - P_0}{P_0 - P_s} \]

where \( P_{\text{sensor}} \), \( P_0 \) and \( P_s \) are the pressure measured by the probe, the stagnation pressure and the static pressure respectively. When the sensor faces the flow, the inlet stagnation pressure is measured. As the probe is rotated about its stem, the pressure falls to a minimum at about ±83°. Outside this range, the sensor indicates a relatively constant base pressure.

In the case of the pressure probe, the calibration is assumed to be independent of the dynamic head and so the quantity

\[ \langle \chi^2 \rangle = \sum_i \left( \langle E_i \rangle - \left( \langle p_0 - p_s \rangle f(\theta, \xi) + \langle p_0 \rangle \right) \right)^2 \]

was minimised where \( f \) is the function indicated in Fig. 4. A comparison with the similar expression for the hot wire anemometer shows that the additional quantity to be determined is represented by the fact that the stagnation pressure will be different to that in the calibration. In this application, the asymmetry noted above and the relatively small capture angle are of little consequence. Providing the probe has an angular sensitivity over the range of angles selected, then each measurement will make a useful contribution to the evaluation of the minimum value of \( \langle \chi^2 \rangle \). Therefore, the capture angle is approximately ±83° and the concept of unambiguity (see Humm et al (1995)) is irrelevant. Indeed, providing the calibration curves for forward and reversed flow are dissimilar, it is possible to unambiguously determine if there is reversed flow when sufficient probe angles are used over a wide enough range. In this context it may be noted that using the implicit method described above provides a larger capture angle than using the conventional explicit method. It also suggests that the potential benefits of the Least Squares Method are far greater when applied to a pressure probe data than when applied to hot wire data.

**Fig. 4 Angular calibration for pressure probe**

A Virtual Flow

To assess the application of the method of least squares, a series of virtual 2-dimensional experiments have been conducted. The two-dimensional velocity vector is described by the following equations

\[ U = 5 + u \]
\[ V = 10 \sin \phi + v = 10 \sin \omega t + v \]

where \( \phi \) is the phase angle, \( \omega \) is the periodic frequency of oscillations in the flow and \( u \) and \( v \) have Gaussian probability distributions such that

\[ \sqrt{\frac{\sigma_u^2}{\mu_u^2}} = \sqrt{\frac{\sigma_v^2}{\mu_v^2}} = 3 \]

The time-mean velocity is in the reference (axial) direction. The phase-lock-averaged flow angle varies from −63.4° through zero to +63.4°. The magnitude of the phase-lock-averaged velocity varies from 5 to 11.2 m/s. The above velocity variation is deliberately large.

1 The “Least-Squares” method of data reduction could also be applied to a multi sensor probe. In that case the concept of capture angle would have to be significantly revised.
When a probe is placed close behind a rotor in the hub or casing region, changes of this magnitude are possible near to the trailing edge of the blades. Fig. 5 illustrates how the velocity components vary over one cycle for various ensembles. Much of the emphasis below is placed upon the accurate determination of the flow angle. This is partly for the sake of brevity but also because the determination of the flow angle is more difficult than the determination of the velocity or the dynamic pressure.

**Assessment of Least-Squares Method of Data Reduction using the Virtual Flow**

The experimental programme was conducted in the following way. In a given experiment, the sensor was placed at several different angles with respect to the reference direction. The angles were chosen so that the angle between the reference direction and the sensor normal direction was in the range $-90^\circ < \xi \leq 90^\circ$. This range was divided in equi-spaced intervals. Since the response of the sensor at $90^\circ$ is nominally the same as at $-90^\circ$, measurements were not repeated at $-90^\circ$. Prior to the application of the least-squares method, the raw data obtained at each sensor position and phase angle was phase-lock-averaged.

The experiments were repeated for a range of “total costs”. This total is the product of the number of sensor positions and the number of ensembles acquired at each sensor position. To further evaluate the technique, the experiment was repeated at a given total cost with the sensor placed at 4, 8, 16, 32, …, etc equi-spaced positions. Finally, each experiment as defined by its total cost and the number of sensor positions was repeated 100 times. By analysing the results for each of these 100 repeated experiments, the systematic errors and the random error (standard deviation) could be evaluated. The random error is defined as the standard deviation that results from the variability in the phase-lock-averaged data. The systematic error is defined as the standard deviation that results from comparing the true result over one periodic cycle to that indicated by the measurements.

For every data set the minimum value of $\chi^2$ is sought for each phase angle. In the case of the hot wire anemometer, Fig. 6 shows how $\chi^2$ varies as the angle of offset which is equal to the flow angle $\theta$ and the value of the scale factor which is equal to $\langle C \rangle$ is varied over the range of the search. Almost any search algorithm will be successful in locating the absolute minimum since there is only one minimum. Even in the presence of the effects of turbulence, this appears to be the case providing a sufficient number of ensembles are acquired. It is also true for the pressure probes considered below. Having found the minimum value of $\chi^2$, the values of $\langle C \rangle$ and of $\langle \theta \rangle$ for each phase angle can be determined and the experiment is complete.

**Fig. 5 Typical velocity components for virtual experiment, hot wire anemometer**

**Fig. 6 $\chi^2$ for a fixed phase angle for a total cost of 8192 ensembles and 32 sensor positions, hot wire anemometer**

Fig. 7 shows the variation in flow angle as obtained when using 4 and 16 positions of the sensor. The total cost of each experiment was 512 ensembles. In the case of 4 positions, 128 ensembles were acquired at each position. In the case of 16 positions, only 32 ensembles were acquired at each position. Nevertheless, the data obtained with 16 positions is much closer to the true answer. Clearly, the number of sensor positions affects the accuracy of the data. This is primarily because of the turbulent fluctuations. In the absence of these fluctuations, the error is negligible, irrespective of the number of positions employed.

**Fig. 7 Ensemble-mean flow angle variation derived from “Least-Squares” method for total cost of 512 ensembles at each time level, hot wire anemometer**

Fig. 8 and Fig. 9 may be used to assess the effect of the number of sensor positions and the total cost (64 to 512 ensembles) on the accuracy of the measured flow angle. Fig. 8 shows the results of the hot wire investigation. Fig. 9 shows the results of the pressure probe investigation. Because the random error will depend on the magnitude of the turbulence and the number of ensembles acquired,
its absolute magnitude should not be compared to that of the systematic errors.

Fig. 8 and Fig. 9 indicate that in order to minimise the systematic error in the measurement of flow angle, at least 16 sensor positions should be employed. This is irrespective of the total cost. This is a far greater number of positions than the publications on this technique have suggested. In practical terms, the accuracy is independent of the number of sensor positions above 16. Above this limit, the accuracy only depends on the total cost. In less turbulent and/or unsteady flows, the systematic errors are reduced but fewer positions should not be used. The random error is effectively independent of the number of sensor positions. However, its magnitude does depend on the turbulence level within the flow. Fig. 10 shows the systematic error for a given total cost of 512 in the case of the pressure probe. For most turbomachinery applications (turbulence greater than 10%) the systematic errors seem to be almost linearly dependent on the effects of turbulence. Below 10% turbulence the systematic error asymptotes to a small value of 0.1°, which is most likely due to truncation errors.

For most turbomachinery applications (turbulence greater than 10%) the number of ensembles that would be employed when using a multi-sensor probe multiplied by the number of sensors? are also plotted. Fig. 11 shows that for both types of probes, as expected, the random errors vary in proportion to the reciprocal of the square-root of the total cost. In the case of the pressure probe, the random errors are greater than those produced by the hot wire. The systematic errors that arise from the pressure probe experiments are also greater than those produced by the hot wire. These differences are mainly due to the fact that three measurements are now required to determine the flow. In the case of the pressure probe, the systematic errors are typically of the order of 0.7-0.9°. However, they are much less dependent on the total cost than in the case of the hot wire.

Fig. 11 confirms that once sufficient sensor positions are employed, the normal rules governing the number of ensembles that are required to obtain a given level of certainty may be applied. The only issue that now remains to be resolved is to determine whether the number of ensembles required is greater than the minimum that is strictly necessary. In other words, is the total cost greater than the number of ensembles that would be employed when using a multi-sensor probe multiplied by the number of sensors?

Comparison with conventional data reduction method

Fig. 12 presents the result of processing the data from the experiments described above using a conventional approach for the hot wire data. The data shown is equivalent to the random error data shown in Fig. 11. Two sets of data are shown for each experimental configuration. The reasons for this are described below.

In the conventional approach, orthogonal sensor pairs are used to determine the local flow angle. At each phase angle, the results from each pair are examined to determine which pair is best conditioned. Under these circumstances, the outputs from each sensor in the pair are approximately equal. Each sensor pair yields a flow angle magnitude and a velocity magnitude. Since a single pair cannot be used to determine which quadrant the flow vector lies within, the result from the sensor pair which is at 45° to the chosen pair is used to determine the quadrant. Effectively, a minimum of 4 sensor positions are used.

Unfortunately, there is a problem with the conventional data reduction technique as described above, because a decision must be made regarding which pair of sensors should be used. Furthermore because the flow is turbulent, the algorithm does not always choose the same pair of sensors when two pairs of sensors should be equally suitable. As a consequence, the flow angle determination is less certain near to these decision points. This serves to increase the
random errors as well as the systematic errors. The open symbols represent this situation. If the data obtained near the decision points are removed, then the solid symbols are obtained. In practice, this would require a complex algorithm even in a two dimensional flow. It was this single fact that originally prompted the authors to search for an alternative data reduction algorithm.

Though not presented here, the conventional technique yielded systematic errors that were essentially dependent only on the number of wire positions. The best case scenario yielded a systematic error of 0.4°. If all the data are considered, the systematic error is approximately 4° due to large errors in the determination of the angle near the decision points. The complex algorithms required to avoid these large systematic errors further supports the suggestion that the least squares method is preferable for both types of probes reported here.

**APPLICATION OF THE LEAST SQUARES METHOD IN A RADIAL FLOW TURBINE**

A final test for evaluation of the new pressure probe and the application of the Least Squares method was conducted in a large scale radial inflow turbine. The radial inflow turbine has been described in detail by Huntsman et al. (1991, 1993). It operates in an open loop configuration and the mass flow rate is controlled by a throttle situated downstream of the turbine. The hot-wire anemometer and the single-sensor fast response pressure probe were traversed at exit of the rotor. As indicated in Fig. 13 the traverse plane is located at 116 % meridional length, measured along the casing.

Two rotor passages of 33 radial immersions and 128 pitchwise points were traversed by both probes. At each immersion the probe was turned around its own axis and data at 16 positions was acquired. The data was processed with the Least-Squares method as described above. The range of the piezo-resistive transducer is +/- 35 000 Pa. The measured dynamic head at exit to the rotor of the radial inflow turbine is between 10 and 150 Pa. Despite of the low sensitivity of the pressure probe, a successful application is demonstrated here.

Measurement errors arising from the effects of flow unsteadiness on the probe are not an issue in the present circumstances. At a rotational speed of 450 rpm, the blade passing frequency of the radial turbine is 7.5 Hz. The reduced frequency based on the probe diameter and a mean flow velocity at rotor exit was calculated to be 0.003. Hence, the probe will respond to the flow in a quasi-steady manner. Furthermore, measurement errors due to vortex shedding from the probe stem were also found negligible. In a flow where the RMS fluctuation were of the order of 2% of dynamic head, no vortex shedding could be detected in the frequency spectrum.

Because only one pair of readings is used to determine the magnitude of the flow angle and the velocity, the data trends shown in Fig. 12 are different to those exhibited by the least-squares method. Fig. 12 shows that for a given total cost, the random error is reduced as the number of sensor positions is reduced. This is because the number of ensembles acquired at each sensor position is increased. Therefore, the quality of the data obtained for each pair of positions is also increased. However, the random errors obtained when using 4 or more sensor positions are never lower than those obtained using the least-squares method. This is because there is always redundant data. In fact, if the velocity data were to lie in only one quadrant, only two sensor positions would be required. It is only under these circumstances that the random errors would be less than those arising from the least-squares method. This will generally not be the case. Fig. 12 therefore confirms that the total cost of using the least-squares method is never greater than that which would arise when using a multi-sensor probe multiplied by the number of sensors. It is also interesting to note that Fig. 12 suggests that no more than 4 wire positions should be employed when using the conventional technique.
When designing the turbine Huntsman (1993) prescribed a negative swirl of –26 degrees at a given rms radius of 0.75 \( r/r_{tip} \). The tip clearance has been doubled relative to the original rotor design, but it was to be expected that this should not affect the flow in the lower half of the blade span at rotor exit. Indeed Fig. 14 shows a negative swirl of about -25 degrees between the hub and 0.75 \( r/r_{tip} \). The flow towards the casing is however dominated by large tip clearance flow features. In order to show these features more clearly, the data has to be transformed into the relative frame.

In theory the present pressure probe can also be used to measure the rotor exit stagnation pressure. However the data is not presented here. The absolute velocities at rotor exit are below 10 m/s near the casing so that loss measurements require a very high sensitivity. Unfortunately, the probe is very sensitive to changes in temperature. The change in temperature that occurs across the turbine and the change in temperature that occurs as the sensor is cooled by the flow (though small, the energy input is significant) would have to be accounted for in the calibration. This was beyond the scope of the present project, but will be addressed in future work.

**Fig. 14 Radial variation of pitchwise averages**

Fig. 15 shows a comparison of the pitchwise averaged relative angle. The blade angle at exit of the rotor is indicated by the dashed line. Both measurement techniques indicate a pitchwise averaged relative flow angle similar to the blade angle between the hub and midspan. The reason why the exit flow is so well behaved is because the flow is virtually loss free near the hub due to the absence of secondary flow phenomena. The high turning of the flow is also due to the fact that the rotor boundary layers are very thin for the present radial turbine (Huntsman, 1993).

Near the casing Fig. 15 reveals the presence of a tip vortex structure which is coincident with the location of the minimum velocity (see Fig. 14). The measurements indicate a region of overturning and a region of underturning relative to the mean flow field near the casing. The gradient in between these two regions indicates the core of the vortex near \( r/r_{tip} = 0.9 \). The vortex is associated with low momentum fluid originating from the mixing process of tip clearance fluid and main stream flow. This region at exit of the radial turbine presents a difficult test case for any experimental method. The results shown above confirm the successful implementation of both the new probe and the application of the Least Squares method.

**CONCLUSIONS**

The Least Squares method was successfully applied in two experiments. The beauty of the method lies in the fact that there is no redundancy of data. The total cost (ensembles x orientations) of the new method is never greater than the cost using a conventional method of data reduction. Nor is it greater than the cost of using a multi-sensor probe multiplied by the number of unknowns.

The accuracy of the method mainly depends on the turbulence intensity of the flow and the total cost. The Least Squares method does not require unambiguous pressure coefficients. Hence it also extends the useful range of probes to a maximum. Another advantage is that since the experiment is mapped onto the calibration, the Least Squares method depends less on random errors in calibration. It is also much simpler to implement in software. It was found that the best results are achieved when the probe is placed in at least 16 different orientations.

The ultimate test for the new probe and the application of the Least Squares method was considered to be the data acquisition behind the rotor of a radial inflow turbine. A single axis hot-wire anemometer and a single-sensor fast response pressure probe were compared in the same flow field. All of the flow features were captured and the comparisons were found to be satisfactory.

**REFERENCES**


